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Tests of an Improved Oceanographic Expert System

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For 8 years the Naval Research Laboratory's Remote Sensing Applications Branch has been developing an oceanographic expert system (OES) that models some aspects of the kinematics of the Gulf Stream and its associated eddies. The OES uses a rule base to provide ring-motion forecasts and a neural network to forecast Gulf Stream motion. Previous work showed that OES forecasts of ring motion are at least as good as those produced by other methods. Recent work led to improvements in the ring-motion geometry equations, replacement of the Gulf Stream motion logic, and the addition of a natural-language explanation facility. The first two changes required "retuning" of the OES. The changes were designed to remove linear trends in the mean forecast position errors for noninteracting (with the Gulf Stream) rings. This report presents a comparison of the present system's performance with "prototype" and improved parameters. For noninteracting rings, the improved system provides ring-motion forecasts that are superior to a no-motion assumption 75% or more of the time for both warm-core rings and cold-core rings, for both 7-day and 14-day forecasts. The forecast ring positions are within 20 km of the true positions. This report provides more complete information on the OES and the test results.

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Tests of an Improved Oceanographic Expert System

Introduction

The oceanographic expert system (OES) developed by the Naval Research Laboratory's Remote Sensing Applications Branch models some aspects of the kinematics of Gulf Stream mesoscale features. As part of a suite of tools to assist the satellite image analyst, it models the motion of warm-core and cold-core rings (WCRs and CCRs), and, to a lesser extent, the motion of the Gulf Stream (Thomason and Blake 1986; Thomason 1989).

The OES uses a rule base to provide location-dependent ring-motion forecasts. Motions hypothesized by the OES are further modified by ring-Gulf Stream interactions. Consequently, the OES also requires the Gulf Stream's position as a function of time. Originally, the OES used a simple model of Gulf Stream motion in terms of downstream propagation of meanders. Now it uses a neural-network-based forecast module, which provides better motion estimates.

The OES performed well in comparison with conventional numerical models (Lybanon and Thompson 1991), but development has continued. One change improved the geometry used to describe ring motion. A "natural language" explanation facility permits the user to interrogate the system to find out why it projected a particular motion (Bridges 1992; Bridges and Lybanon 1993). A recent conversion into a C-based language is intended to make the OES easier to implement on a variety of platforms (Bridges and Chen 1994).

Expert System

The OES's domain is the northwest Atlantic Ocean. That domain is divided into nine geographic regions. In each region the OES "moves" rings in the same fashion. The basic motion is at a specific speed in a specific direction; those values differ from one region to another and for WCRs and CCRs. If a ring is "close" to the Gulf Stream, then the ring is assumed to be interacting with the Gulf Stream and its motion is modified. The closeness criterion and the details of the interacting motion also differ from one region to another and for WCRs and CCRs. This characteristic of the OES allows the ring motion rules to be general, with the details specified by values in a "region parameters" file. As a consequence, changes to the way the OES moves rings can be made simply by changing region parameters. That feature allows improvements to be made without the necessity of recompiling (Lybanon 1990).

The region parameters file contains a set of values for each of the regions and for each type of ring, warm and cold. Thus, there are 18 sets of values. Each set includes an identifier, a speed (for noninteracting ring motion), a number from 1 to 16 indicating general direction (used by the interacting ring motion rules), a compass heading, a size decay factor for noninteracting rings, a minimum radius below which a ring is assumed to coalesce with the Gulf Stream, and a decay factor for interacting rings. In addition there are "breakpoints," three each for warm rings and four each for cold rings, used by the interacting ring rules.

The simplest change to the region parameters file is "global" improvement, designed to minimize the average (over all WCRs and over all CCRs) errors in forecast ring position. The changes were based on tests, in which ring positions forecast by the OES were compared with the observed positions of the same rings at the later times. The tests and the error measures are discussed in greater detail in the next section. The global improvement consisted of one vector change in ring

velocity for all WCR regions and a similar change for all CCR regions. The speed and compass heading parameters are the parameters that were changed. The purpose of the change was to remove linear trends in mean vector position errors. Only noninteracting (with the Gulf Stream) rings were considered, and only the "noninteracting" region parameters were changed. The Results section of this report compares the results obtained for both the original ("prototype") and improved (designated "Mod 5") OES versions.

Several changes were made in the OES itself, which has been under development for 8 years. Earlier versions of the OES, and its performance, are described in the references (Thomason and Blake 1986; Lybanon 1990; Lybanon and Thompson 1991). As pointed out in the Introduction, the changes included improvements in the ring motion geometry equations, the addition of a natural-language explanation facility, replacement of the Gulf Stream motion logic, and ongoing conversion into a C-based language.

The original OES did not distinguish between the different sizes of a degree of latitude and a degree of longitude, nor did it account for the variation with latitude of the latter size. To first order that is an unimportant error. Since the latitude extent of a single region is small, the size of a degree of longitude is nearly constant within a region and the error can be compensated to a good approximation by properly ("improperly" more accurately describes the situation) defining the region parameters. For this reason, it was possible to get reasonably good performance from the OES. However, the error made it difficult to calculate and apply the global improvement corrections described above. Also, the same distance calculation was used to find the distance between a ring and the Gulf Stream. Since this distance is used to determine whether a ring is interacting with the Gulf Stream, that decision was erroneous in some cases. The geometry error has been corrected both in the (noninteracting) ring-motion rules and in distance calculations. Bridges (1992) gives details of the changes.

The explanation capability was added to give users a basis for judging the quality of the system's decision-making process. It also makes it easy to distinguish between interacting and noninteracting rings, and to obtain other information used in the evaluation tests. The explanation component consists of an introspection module and a presentation module. The former "watches" the reasoning process and records the data that caused each rule to fire and the new information produced as a result of each rule firing. The latter can use this information to present a detailed natural language trace of the rules that have fired or a shorter natural language summary of the reasoning used for the prediction. The structure of the original OES was not amenable to the incorporation of an explanation facility because the knowledge needed for explanation was not explicitly represented in the knowledge base. So, prior to implementing the explanation facility, the structure of the rule base was revised with the knowledge "chunks" in each rule at a finer level of granularity, and the results of each decision explicitly asserted into the working memory. Although the new rule base actually contains more rules than the old one, the rules are more general. Not only will possible future modifications be facilitated, but the system's speed increased slightly (Bridges 1992; Bridges and Lybanon 1993).

The simple Gulf Stream motion module was replaced by an improved version that uses a neural network to forecast changes in Gulf Stream shape (Chase and Holyer 1993). Another change will make it easier to "port" the OES to other Navy facilities, e.g. as a part of the Tactical Environmental Support System (Lybanon 1992). The OES was originally written in a combination of OPS83 (a specialized expert system language), C, and Fortran. The modifications described above were made in those languages, and the resulting modified OES was used in the tests described in the next section. However, a recent effort converted the rule-based portion of the OES into the C Language Integrated Production System (CLIPS, an expert system tool developed

by NASA) and the procedural OPS83 code into C. The converted system will be able to run on any computer that has a C compiler, and it will be functionally identical to the OPS83 version (barring any future modifications).

Results

The geometry changes guaranteed that the OES would give different hypothesized ring positions than the previous versions, so it was necessary to "tune" the system. This was done by reverting to the "prototype" region parameters, testing the modified OES, and using the "global improvement" technique to determine a new region parameter set.

Tests consisted of comparing OES forecasts for 7 and 14 days with observed ring positions and sizes at the same later times. Analysis used several error measures: "goodness-of-fit" measures for both position and size, the number of cases for which the OES's position forecasts were more accurate than a no-motion assumption, and vector and scalar position errors.

The goodness-of-fit measure for ring position is simply the ratio of the error in the forecast ring position to the total distance moved by the ring in the time interval (7 or 14 days in these tests), or

$$GOF_{translation} = \text{(position error)} / \text{(distance moved)}.$$

Similarly the goodness-of-fit measure for ring size is the absolute value of the fractional error in ring size for the later time, or

$$GOF_{size} = |1 - r_{forecast} / r_{actual}|.$$

In both cases, small values indicate accurate forecasts. Zero values mean a perfect match between the forecast position or size and the observed value for that time. That observation applied to $GOF_{translation}$ leads to the definition of another error measure.

$GOF_{translation} = 0$ indicates a perfectly accurate position forecast. A no-motion forecast translates into $GOF_{translation} = 1$, since in this case the distance the ring actually moves is the error in forecast position. So it is clear that $GOF_{translation}$ values less than 1 correspond to forecasts that are more accurate than those given by the no-motion assumption, while values greater than 1 correspond to less accurate forecasts. Because of this, the percentage of cases in which the OES's forecasts are better than a no-motion assumption is easy to find.

One number does not adequately characterize a data set, so the analysis of test results employed several other error measures. One is the mean value of $GOF_{translation}$. Position errors themselves are meaningful. The numerator of $GOF_{translation}$ is scalar position error, so that quantity is immediately available. One might argue that mean scalar position error overstates the error, since all of the individual values are positive, regardless of direction. To take account of this objection, the mean vector position error is also reported. This calculation resolves each error into x and y components, which are separately averaged over the data set. The resulting mean vector error has the property that errors in one direction are compensated by errors in the opposite direction. Random (small, it is hoped) errors are expected to average out, leaving only overall biases. So the

combination of vector and scalar errors gives information both on bias and scatter in the position errors.

Figure 1 shows the region parameters file with "prototype" (i.e., those from the original version of the system) values. Tests of the OES using this regions file, using the "Gulfcast" data set described in Lybanon (1990), were evaluated using all of the error measures described above. Only noninteracting ring cases went into the statistics. A fit to the mean values (over all noninteracting WCRs and CCRs) of the vector error components, for 7- and 14-day comparisons, yielded vector error velocity estimates for WCRs and CCRs. That is, the linear trend coefficients for Δx and Δy are effectively the components of the velocity with which the OES forecasts deviate, on the average, from ground truth. The global correction consisted of using these velocities to correct the speed and compass heading parameters, yielding the Mod 5 region parameters file shown in Fig. 2. This "Mod 5 system" was tested against the same data set.

Table 1 shows the statistics that result from the tests of both the prototype (upper part of table) and Mod 5 (lower part of table) versions of the OES. In all cases the ring-size results show that the OES (both versions) predicts ring size accurately. The ring-motion results are a different matter. The prototype system achieved better results for CCRs than WCRs. For CCRs, the percent better than no motion statistics were higher than 50% for both 7 and 14 days, and the mean $GOF_{translation}$ statistics were less than 1.0 for both 7 and 14 days; the opposite was true for WCRs. The scalar and vector error magnitudes of mean position error were better for CCRs than for WCRs, also. However, the Mod 5 system outperformed the prototype system with respect to every single one of the motion error statistics. In particular, the vector error magnitude values were drastically reduced. This is not surprising, since the global correction was designed to accomplish exactly this result. The Mod 5 ring-size error statistics were very similar to those for the prototype system. While the greatest improvement took place in the WCR ring-motion statistics, the CCR ring-motion statistics were also significantly improved.

Comparison with previous results (Lybanon and Thompson 1991) shows that the OES with the "wrong" geometry apparently obtained better results, at least with respect to some of the error measures, for both WCRs (with Mod 4 parameters) and CCRs (with Mod 3 parameters). Why then should we not restore the previous motion geometry and use the parameters that give superior performance, despite the fact that (theoretically, at least) the old motion geometry was wrong? This procedure is rejected on two counts. First, the old results are not significantly better than the new results (and are sometimes worse), especially considering the small size of the test data set. (It may even be true that the old results appear better than they really are because some noninteracting rings were incorrectly labeled as interacting; hence, they were mistakenly eliminated from consideration.) Second, the old results came after several stages of improvement, whereas the results tabulated in Table 1 came after only one stage of improvement. It is reasonable to assume that further improvement is possible, and the benefits of using the correct motion geometry are judged to outweigh the apparent benefit of the (apparently) slightly better results obtained previously.

Conclusion

The work presented here shows that the expert system is "trainable." The modifications made so far amount to first-order corrections. The Mod 5 changes to region parameters effectively remove the linear trend from both WCR and CCR motion errors, and the paths predicted by the expert system are superior to a persistence (no motion) assumption 75% or more of the time for

both WCRs and CCRs, for both 7-day and 14-day forecasts. The mean scalar position errors, which give a measure of scatter of the forecast positions about the true paths, are of order 20 km for 14-day forecasts, and less for 7-day forecasts. The expert system shows promise as a natural complement to a full numerical model formulation in the operational forecasting of ring motion.

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WREG1	8.0	1	0.0	0.5	100.	0.5	.9	.75	.5	
WREG2	8.0	9	210.0	0.9	30.	0.8	.9	.75	.5	
WREG3	8.0	10	240.0	0.95	30.	0.85	.9	.75	.5	
WREG4	6.0	12	260.0	0.99	35.	0.96	.9	.75	.5	
WREG5	7.5	11	244.0	0.998	30.	0.98	.9	.75	.5	
WREG6	6.0	12	249.0	0.998	30.	0.98	.9	.75	.5	
WREG7	5.0	13	264.0	0.999	30.	0.98	.9	.75	.5	
WREG8	5.0	13	267.0	0.999	35.	0.98	.9	.75	.5	
WREG9	5.0	13	268.0	0.999	35.	0.98	.9	.75	.5	
CREG1	6.0	10	267.0	0.998	25.	0.8	0.3	0.31	0.8	0.
CREG2	6.0	10	249.0	0.998	25.	0.9	0.3	0.31	0.8	0.
CREG3	6.0	7	249.0	0.998	25.	0.9	0.3	0.31	0.8	0.
CREG4	6.0	10	260.0	0.999	25.	0.95	0.3	0.31	0.8	0.
CREG5	5.0	11	264.0	0.999	25.	0.95	0.3	0.31	0.8	0.
CREG6	5.0	11	264.0	0.999	30.	0.95	0.3	0.31	0.8	0.
CREG7	5.0	11	264.0	0.9999	35.	0.98	0.3	0.31	0.8	0.
CREG8	5.0	12	264.0	0.9999	35.	0.98	0.75	0.751	0.9	0.
CREG9	5.0	13	264.0	0.9999	35.	0.98	0.75	0.751	0.95	0.

Modified by Susan Bridges 7/31/91. The lat adjust and long adjust factors described below have been replaced by one heading value that corresponds to a compass heading.
Items per line are region name, speed (cm/sec), direction (one of 16 for general reference), lat adjust factor*, long adjust*, decay when not in GSinteract, min radius for no coalesce with GS, decay in GSinteract.

For wcregions, also breakpoints b1-3 for ratio tests in GS interaction.

For ccregions, also breakpoints b1-4 for ratio tests for looping effects.

Further modified by Matthew Lybanon 2/2/93 to correct some minor apparent discrepancies.

*These are the 2 quantities that have been replaced by compass heading.

Figure 1. Region parameters file with "prototype" parameter values.

WREG1	10.1	1	20	0.5	100.	0.	.9	.75	.5		
WREG2	5.51	9	186	0.9	30.	0.8	.9	.75	.5		
WREG3	4.32	10	234	0.95	30.	0.85	.9	.75	.5		
WREG4	2.50	12	280	0.99	35.	0.96	.9	.75	.5		
WREG5	3.77	11	241	0.998	30.	0.98	.9	.75	.5		
WREG6	2.27	12	252	0.998	30.	0.98	.9	.75	.5		
WREG7	1.79	13	301	0.999	30.	0.98	.9	.75	.5		
WREG8	1.95	13	307	0.999	35.	0.98	.9	.75	.5		
WREG9	2.01	13	309	0.999	35.	0.98	.9	.75	.5		
CREG1	4.21	10	269	0.998	25.	0.8	0.3	0.31	0.8	0.	
CREG2	4.28	10	243	0.998	25.	0.9	0.3	0.31	0.8	0.	
CREG3	4.28	7	243	0.998	25.	0.9	0.3	0.31	0.8	0.	
CREG4	4.21	10	259	0.999	25.	0.95	0.3	0.31	0.8	0.	
CREG5	3.21	11	265	0.999	25.	0.95	0.3	0.31	0.8	0.	
CREG6	3.21	11	265	0.999	30.	0.95	0.3	0.31	0.8	0.	
CREG7	3.21	11	265	0.9999	35.	0.98	0.3	0.31	0.8	0.	
CREG8	3.21	12	265	0.9999	35.	0.98	0.75	0.751	0.9	0.	
CREG9	3.21	13	265	0.9999	35.	0.98	0.75	0.751	0.95	0.	

This file was prepared 10/19/93.

Items per line are region name, speed (cm/sec), direction (one of 16 for general reference), heading, decay when not in GSinteract, min radius for no coalesce with GS, decay in GSinteract.

For wcregions, also breakpoints b1-3 for ratio tests in GS interaction.

For ccregions, also breakpoints b1-4 for ratio tests for looping effects.

This version of REGIONS.DAT contains "mod 5" changes. These are chosen to remove the global linear trends from the results of applying the "prototype" version to noninteracting (with the Gulf Stream) rings only, after Susan Bridges put the motion geometry corrections into the expert system. The corrections came from a 2-parameter linear fit to the errors.

Figure 2. Region parameters file with "Mod 5" parameter values.

Table 1. Prototype and Mod 5 System Test Statistics

Days	WCR/CCR	Number of Rings	Percent better than no motion	Mean GOF size	Mean GOF Translation	Mean Pos. Errors Scalar	Mean Pos. Errors Vector Magnitude
			Prototype System Results				
7	WCR	23	40.91%	0.011	1.729	24.768	21.64
	CCR	28	60.71%	0.021	0.941	23.812	10.15
	total	51	52.00%				
14	WCR	9	22.22%	0.032	1.896	48.225	44.23
	CCR	8	75.00%	0.012	0.698	30.45	20.85
	total	17	47.06%				
			Mod 5 System Results				
7	WCR	22	85.71%	0.012	0.784	13.244	1.71
	CCR	27	77.78%	0.022	0.603	19.804	2.87
	total	49	81.25%				
14	WCR	8	75.00%	0.029	0.752	22.181	4.96
	CCR	9	88.89%	0.024	0.415	20.832	2.5
	total	17	82.35%				

GOF = goodness of fit   Position errors in km